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6 CLOSED CYCLE GAS TURBINE SYSTEMS IN EUROPE

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A review on the status of closed cycle turbine research and development in Europe is given. Closed cycle turbines utilizing air as a working fluid, either coal, gas or oil fired have been used in the past for electricity generation and as additional sources for district heating. The newer developments employ helium as a working fluid. The gas is heated by a large sophisticated gas heater at present. However, the final intention is to use turbines in connection with the high temperature gas cooled nuclear reactors. Marine applications for gas turbines exist and are discussed in the report.

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CLOSED CYCLE GAS TURBINE SYSTEMS IN EUROPE

I. Introduction

At the turn of the century, the steam turbine began to emerge and subsequently forced the steam engine off the market. Although the advantages of the turbine are numerous and obvious, it took a long time to displace the engine; as a matter of fact, steam engines (at this stage called steam motors) were still being manufactured and sold in Europe for some time after WWII.

A similar phenomena is taking place in the competition between the (open-cycle) gas turbine and the reciprocating internal combustion engine. Although in this jet-age, the advantages of gas turbines are well known, the internal combustion engine has not been completely replaced yet, not even in aeronautics let alone other more mundane applications. The reason is that for every advantage in technology there is also a disadvantage. In the case of the gas turbine-piston engine competition, these trade-offs are less pronounced, particularly in the low horsepower range, and the issue is no longer as clear-cut as it was in the steam turbine-steam engine contest.

Now it seems that a new race is emerging, -- the competition between open- and closed-cycle gas turbines. And here the issue is even more clouded. It is the purpose of this report to review the current state of the contest in Europe with regard to central station power plants and discuss the issues involved.

Historically, the close-cycle gas-turbine (CCGT) concept began to emerge about 35 years ago (see for example, Ref. 1). The world's first industrial closed-cycle gas turbine was built in 1956 in Ravensburg, Germany, and has been operating successfully since that time. This turbine is fossil-fuel fired. With the advent of the high-temperature nuclear gas-cooled reactors (HTR, AVR, HTGR, THTR), the closed-cycle helium gas-turbine concept has been attracting considerable interest and has been seriously discussed during the past ten years. The reason, in part, is its potential for direct integration with selected high-temperature gas-cooled reactors, thereby eliminating the intermediate heat exchangers; this could lead to more efficient yet lower-cost power-conversion systems requiring little or no cooling water supply for heat rejection. At present, the gas-cooled reactors require heat exchangers to generate steam which, in turn, drives a steam turbine. However, the next generation gas-cooled reactors, if built, could use the closed-cycle gas turbines. Therefore, the race is really on between steam turbine and closed-cycle gas turbine, at least in the central-station nuclear power-plant business.

II. Today's Issues

Today's issues vary somewhat depending on the application, but the basic problems are the same. First, consider the nuclear central-station power-plant application. Here the issue is a boiling- or pressurized-water reactor with steam cycle versus a gas-cooled reactor with closed helium-turbine cycle. As a side issue, one could include the gas-cooled reactor with a steam cycle versus one with a closed helium-turbine cycle. Next, consider the application for conventional central-power generation. Here it is a choice between a fossil-fueled steam-generator integrated with a steam turbine versus a fossil-fueled (coal) heater integrated with a closed-cycle helium-turbine (which is one way to operate a gas turbine with coal). Last, but not least, there is the marine application, and of course, the conventional arrangement is a boiler with steam turbine, the alternative being an open-cycle gas turbine. It is a true alternative since the steam cycles are mostly oil fired, while the gas turbines burn oil internally thus often requiring fuel of substantially higher grades. The feasibility of using a closed-cycle gas turbine in ships is, at present, an important question which needs to be resolved.

The issues are most readily understood in the case of central-station nuclear-power plants. If gas-cooled reactors are to be used, it would be desirable to circulate the reactor coolant, i.e., helium, through a gas turbine rather than through a heat exchanger with attached steam-power system as is now being done in the first-generation gas-cooled reactors. Despite some obvious advantages, the reason why the CCGT has not been built so far is that, at the time the gas-cooled reactors were introduced, the technology of closed-cycle helium turbine was not yet mature and the reactor coolant outlet temperatures were not high enough to warrant efficient and economical operation of a CCGT. The real issue here is the relative advantages of the light-water reactor (BWR or PWR) versus the gas-cooled reactor. The technical advantages of the gas-cooled reactor compared to LWRs for central-station power plants are commonly quoted as: Higher burnup of the nuclear fuel, potentially lower fuel-cycle cost, higher plant thermal efficiency, and less serious emergency core-cooling system requirement. The disadvantages are: Higher construction costs, lower power density and some unresolved technical problems such as distortion of the moderator blocks caused by radiation damage, gas gagging to achieve a flat power-profile across the core, etc. However, the facts of life are that the LWRs are further developed than the gas-cooled reactor and are being sold in quantity for commercial applications, while the high-temperature gas-cooled reactor is still in the demonstration stage.

For application to a fossil-fueled central-power station, a gas heater is required for the closed-cycle gas turbine, analogous to the boiler for the steam turbine. Although both are fossil-fired, the worldwide renewed interest in coal could provoke an increasing interest in the closed-cycle gas turbine, if it can be proven that such a cycle offers economic and environmental advantages compared to the conventional steam cycle.

The helium cycle is, of course, a Brayton type while the steam cycle is a Rankine type. The CCGT can operate at a higher temperature than the steam cycle, therefore offering a potentially higher efficiency. As it does not involve any phase changes, it requires substantial pumping power.

The steam cycle has to operate at a lower temperature (below about 1050°F) due to the materials limitations inherent in the water-steam system, i.e., corrosion and loss of strength associated with elevated temperature. However, it has an obvious advantage of requiring substantially lower pumping power, offering a reasonably attractive station efficiency of up to 40% at moderatly high turbine inlet temperatures around 1000°F.

Modern steam power systems have practically reached their performance limit as their turbine inlet temperatures have been restricted to below about 1050°F because of the above mentioned materials limitations. A turbine inlet condition of 3500 psig/1000°F/1000°F with a station efficiency of approximately 40.5% is generally regarded as the "metallurgical limit" for many years to come. It should be mentioned that the vacuum required in the steam cycle is responsible for the sheer size of condenser and the massive steam turbine.

In contrast, the CCGT can operate efficiently at a much lower turbine inlet pressure (600-1000 psi), which permits the use of thinner tubes, although they are made of more expensive materials in order to resist the higher turbine inlet temperatures (1350°F or higher). Since the optimal expansion ratio is very low (2 to 5 compared to several thousand for the steam turbine), a CCGT is much smaller in size (one quarter or less) compared to a steam turbine of the same output and, furthermore, requires substantially fewer power-system accessories.

Although heat-transfer in helium is inferior to that in steam, the use of thin-wall smaller tubes--possible in the former fluid--often results in more compact CCGT heaters than steam boilers of same thermal capacities. All these add up to the possibility that lightweight CCGT power systems with specific weight (in lb/shp) savings as much as a factor of 5 lighter than steam power systems can be realized. There is still the question regarding the materials capable of operating for the required lifetime at 1500-1800°F, the temperatures required for a CCGT heater. These are substantially higher than the approximately 1000°F in a steam power system.

While specific weight plays only a minor part in the selection of a central power station (higher specific weight means higher initial investment costs), it certainly plays the most crucial role in shipboard applications. Therefore, one would expect that there would be considerable incentive to use CCGT for those naval ships--either fossil- or nuclear-powered--that require lightweight propulsion systems.

From the discussions above, one can sense some of the potential applications of the CCGT systems, one of which is in the nuclear field for direct integration with hightemperature gas-cooled reactors (HTR or HTGR type) to generate central power. The potential economic, environmental and safety advantages for this nuclear power system remain to be demonstrated. Another application is in the fossilfueled central power station, perhaps with extensive wasteheat recovery for district or process heating. In this case, the working fluid can be either helium or air, although the latter has been preferred. Again, this power system has to offer economic or other advantages in order to penetrate the existing power plant market. Still another potential application which has recently been attracting considerable attention is for future naval ships and marine applications. Both fossil and nuclear heat sources can be utilized in this type propulsion system. The issue here rests primarily on the extent to which the specific weight of the total propulsion system can be reduced as compared to the current systems, and on the economic and reliability characteristics of the CCGT propulsion system. The issue also can be affected by the availability or non-availability of certain fuels in the future.

It is conceivable that advancement in gas (helium)-cooled nuclear reactors--particularly in terms of increased reactor-power density combined with development of lightweight, efficient, and reliable closed-cycle gas turbines--could indeed revolutionize ship propulsion.

III. Some Historical Remarks

An attempt to use the closed-cycle helium turbine for ship propulsion would not be new at all. A Swiss turbine manufacturer, Escher-Wyss, designed and manufactured (see Ref. 1, D. Schmid) a 10,000-hp marine closed-cycle gas-turbine propulsion system using air as a working fluid. This System was delivered to the Mitsui Co. in Japan about 20 years ago, but it was never actually put on a ship. The Maritime Gas Cooled Reactor (MGCR) program was actively engaged in closed cycle gas turbine development for ship propulsion from 1958 to 1963.

For central power application, several fossil-fueled closed-cycle gas-turbine plants were constructed during the last 20 years and are still operating. Table I lists most of these plants. The oldest one is the coal-fired plant at Ravensburg, Germany which is a 2.3-MW unit and has operated so far for over 110,000 hrs. The reliability of plant operation has been excellent, and the last overhaul revealed that all components of the plant are still in good condition (Ref. 2).

The direct integration of a closed-cycle gas-turbine power-conversion system with a nuclear reactor became a possibility with the advent of high-temperature gas-cooled reactors (HTR in Germany, ML-1, MGCR, nuclear rocket reactors, and HTGR in the US) capable of operating at coolant outlet temperatures of 1400°F to 4000°F.

It became evident in two international meetings on hightemperature gas-cooled reactor technology (Paris in May 1965 and Jülich in October 1968) and the subsequent NUCLEX ('69, '72 and '75) meetings that besides the potentially lower fuel-cycle cost for the HTR due to higher burn-up of nuclear fuels, the thermal efficiency of CCGT would be higher than for the LWR steam plants; also that the HTGR-CCGT power systems potentially would be smaller in size, cost less, pose a smaller heat rejection problem, and offer the potential of waste heat utilization as an attractive side benefit. Waste heat utilization is one of the major European incentives to pursue the gas-turbine approach for nuclear power systems. Helium has been the unanimous choice as the CCGT working fluid. German and Swiss turbine manufacturers have concluded that large-output CCGT systems, well over 500-MWe unit size can be built with today's technology. A 1200-MWe unit was designed by the then BST* (Switzerland) in collaboration with BBK**(Germany).

In 1958, the German Ministry of Scientific Research initiated, in cooperation with the Swiss gas-turbine manufacturers (then with Escher-Wyss in particular), a long-range development program for HTR in conjunction with the closed-cyle helium gas turbine as part of the 3rd German Nuclear Program. The world's first nuclear gas-turbine plant, using a closed-cycle helium gas turbine directly integrated with the HTR, was ordered on 14 May 1968, by a letter of intent from KSH (Kernkraftwerk Schleswig-Holstein mbH) to Gutenhoffnungshütte (GHH). The order called for the construction of a 25-MWe CCGT plant with a station thermal efficiency of 39% on the site of the research center at Geesthacht at a cost of DM 76 million. While construction of this (Geesthacht) plant was being prepared, development of a larger 600-MWe HTR-CCGT (48% thermal efficiency) was also initiated within the 3rd German Nuclear Program. However, in early 1970 it was said that the German Science Ministry's High-Temperature Reactor Committee restudied the Geesthacht project, and shortly, in May 1970, GHH indicated to the KSH that they were no longer able to fulfill the contract for the design and construction of the plant. The real cause for terminating the Geesthacht project is uncertain, but GHH gave as the reason the difficulties encountered in fuel-element design and fabrication, and also the helium turbomachinery development. Had the Geesthacht plant been built as scheduled, it would have been a major milestone in the history of nuclear power development, demonstrating for the first time the use of gas turbines for generating nuclear power. Needless to say, the larger 600-MWe HTR-CCGT system never got off the drawing board.

Next in line following the Geesthacht project was a fossil-fueled 50-MWe (plus 53.5-MW heating) helium gas-turbine plant in Oberhausen, Germany, built by GHH for Energieversorgung Oberhausen Aktiengesellschaft (EVO). This heat and power plant, which by now has accumulated over 3500 operating hours, was aimed at investigating the individual components of the helium turbomachinery, such as shaft seals, turbineblade cooling and duct design in a real power-plant operation. The plant also has served as a test facility for helium technology required by a larger plant to be built later.

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*BST or Brown Boveri/Sulzer Turbomaschinen, Ltd. which was under a single management until early 1970s and has now split back to BBC and Sulzer Brothers.

**BBK or Brown Boveri/Krupp Reactorbau GmbH was a short-lived company established jointly by BBC and Fried. Krupp in the late 1950s to undertake the 300-MWe THTR (Thorium High-Temperature Reactor) project. BBK was renamed HRB in 1971.

Not only in Switzerland and Germany, but also in England, programs for nuclear gas-turbines have been actively pursued. The multinational "Dragon" project (with headquarters in England) which was recently discontinued had been one of the major driving forces for the HTR-CCGT power systems. Many British studies, however, claimed that it is necessary to operate the CCGT at a higher turbine inlet temperature--above 900°C (1652°F)--in order to achieve significant power-cost advantage over the steam-power systems. This conclusion was in disagreement with the Continental views, which regarded 800-850°C as quite sufficient to produce meaningful economic advantages over the steam systems.

In this connection, the large gas circulator in the British gas-cooled reactors (Magnox stations) should be mentioned. Although they are not gas turbines, *per se*, since they consist only of the compression part of a turbine, experiences gained with these machines show that 30-year maintenance-free operation is possible with such large-scale rotors.

IV. Helium Demonstration Plants

While there are already several demonstration plants in operation for testing a closed-cycle gas-turbine central power station using air as a working fluid (see Table I), there is only one in operation that uses helium as a working fluid. This is the 50-MWe turbine in Oberhausen, Germany. A second facility under construction and close to operation is the HHV (Hochtemperatur Helium Versuchsanlage, High Temperature Helium Test Facility). This plant is intended as a testing facility for components of a closed-cycle helium turbine rather than as a demonstration plant itself.

Oberhausen II

The demonstration plant in Oberhausen may serve as an illustration of a typical closed-cycle helium turbine-system for central power-plant application. Fig. 1 shows such a typical system. The helium is heated in a large gas-heater which is either gas or fossil fired. The hot gas enters the power turbine where some of its enthalpy is converted into mechanical work. After leaving the power turbine, the gas passes through a regenerator, where part of the remaining enthalpy is passed on to the gas entering the helium heater. The remaining waste heat is taken away by the precooler, which may be a cooling tower or a combination of district heating input and cooling tower. The cool gas enters the compressor and is compressed through the regenerator into the gas heater thereby closing the cycle. In some installations there is an intercooler between the compressor stages. Since the gas heats up during compression, the compression efficiency of the down-stream stages drops. This can be remedied by employing an intercooler.

The Oberhausen plant is operated by EVO which is the local utility of the City of Oberhausen, Germany. EVO is owned by RWE (the largest German Utility Company) and the City of Oberhausen on a 50:50 basis. The facility is the first industrial gas-turbine plant using helium as a working fluid, and the experience gained during construction and operation of the plant will be valuable for future high-temperature reactor projects with directly integrated helium turbines. Oberhausen is located in the Ruhr area, the center of heavy industry in Germany. For this reason, coke-oven gas is readily available in the close vicinity, and is, therefore, used as a fuel for the demonstration plant. Construction of the plant was started in 1970 and it became operative in December 1974. The helium turbomachinery was designed and manufactured by GHH (Gutehoffnungshütte), while the helium heater and heat exchangers were manufactured by Sulzer Brothers in Winterthur, Switzerland. The plant was designed to produce 50-MWe power at an efficiency of 32.5% and supply 53.5-MW thermal power for district heating. District heating in the Ruhr area is already an established fact. There is a pipeline network in existence, which connects all the cities in the Ruhr area and delivers heat to commercial, industrial and residential customers. The heat carrier is compressed water (about 8 bar). Therefore, some of the waste heat of the Oberhausen plant is fed into this district heating system.

A relatively low system-pressurization of 27 bar (397 psia) was selected to provide relatively high-volume flow of helium such that the dimensions of the turbine would correspond to a 300-MW power plant. Aside from the size characteristics, the design of the turbomachinery and other power plant components was performed using conditions anticipated to prevail in large closed-cycle helium gas-turbines integrated with high temperature gas-cooled reactors.

The turbomachinery is installed in two casings; the low pressure turbine which drives the alternator at 3000 rpm is housed by itself; whereas the high-pressure turbine is housed in a separate casing along with the low-and high-flow-path-design for the compressor blades. The two shafts are connected through a gear train which transmits little torque under design-point operation. Thus, the machine resists overspeeding due to sudden loss of external loads with dynamic response behavior similar to a single-shaft design. There are five bearings in the turbomachinery, three of which require seals. The turbomachinery was designed to operate at a turbine-inlet temperature of 750°C (1382°F with a lifetime of 100,000 hr and a safety factor of 1.5. The helium flow rate is approximately 84 kg/sec (185 lb/sec). The design point conditions were established considering the use of this turbine type in nuclear power plants over 300-MWe output. The low-pressure turbine thus represents a 300-MWe turbine in size and stresses in the high-pressure turbine are equal to those in a 300-MWe turbine.

The helium heater (see Fig. 2) which burns coke-oven gas was designed and built by Sulzer Brothers to operate at temperatures below 800°C (750°C normal). While air heaters for the other closed-cycle turbine plants were equipped with cooled combustion chambers, similar to steam boilers, the Oberhausen heater is not. The reason is that this heater was designed from the outset for coke-oven gas, where fouling due to slag formation is no problem, thus making it a good simulator of a nuclear reactor but not very helpful for gaining experience with conventional fuels, which cannot be burned directly in a gas turbine. The coke-oven gas is burned nearly stoichiometrically and adiabatically in two pairs of ceramic-lined cylindrical combustors installed horizontally and facing each other. The flue-gas temperature in the combustor is reduced to about 1600°C (2912°F) by flue gas recirculation from the exit end of the combustor before the gas flows through the heater tube banks. The basic idea of this design is to separate the combustion from the heat transfer process; it practically eliminates flame radiation with its associated uncertainties.

The ducting from the helium heater to the turbine inlet serves as a test section for a coaxial gas duct with fiber insulation inside the high-temperature inner pipe; the low-low-temperature helium from the high-pressure compressor flows around the hot pipe to enter the helium heater. The purpose of this test section is to determine the temperature profiles and changes in the insulation material properties with time. It is also used for investigating depressurization in the insulation fibers during operational transients.

The regenerator has a conventional cross-counterflow design with the colder high-pressure helium flowing through 17,000 tubes running from the fixed header to the floating outlet header. The hotter low-pressure helium passes around the tube bundles in the shell side. The regenerator has a diameter of 4.5 m (14.76 ft), is 22 m (72.2 ft) long and weighs 308 tons. Due to the absence of demand for district heating during the summer, waste heat from the power plant is discarded into the atmosphere, first through a dry cooling tower and then a wet cooling tower.

For load control, both bypass and inventory control are used. Load change from full load to idling can be achieved in split-second time, requiring only one-third of the mass flow bypassed; load increase from idling to full load can be achieved in 10 seconds. Inventory control at 20% per minute increase or decrease of system pressure level is possible. Since bypass control causes sharp drop in thermal efficiency, it is used for quick load change only before switching to inventory control for extended operation.

System start-up is achieved by charging the working fluid to 20% level, synchronizing the turbine-generator, then increasing the turbine inlet temperature to 100°C/hr. The start-up of the helium heater, however, requires a rate of 0.5°C/min.

Contact welding is an important problem where hot sliding parts are in contact with each other. No such problem has been encountered to date, perhaps due to relatively low turbine-inlet temperature (below 680°C) operation; tungsten carbide coating (80 μm) was used for the sliding surface between the supporting studs and the inner pipe of the coaxial ducting.

Welded seals are used for flanges; three chanber systems with O-ring oil seals were found to be satisfactory at test pressures up to 80 bar.

The leakage losses in such a system require replenishment of helium and are an economic factor (the reason why air is used in non-nuclear oriented closed-cycle gas-turbine installations). In Oberhausen, this leakage is reportedly kept down to an economic level.

The current status (summer 1976) is that the plant has been operating at a turbine inlet temperature of 680°C (1 (1256°F) generating 12-MWe power with reduced helium-mass flow, dumping 30-MW waste heat into the atmosphere via the cooling towers. The demand for district heating is, of course, low in summer. The previous winter was also very mild. This was given as a reason why the plant has not yet operated at its design load (50 MWe plus 53 MWt). It is expected that it will be operated at full power in the winter of 1976 unless it is another mild winter.

<u>Hochtemperatur Reactor with Helium Turbine (HHT) at the KFA</u>

KFA (Kernforschungsanlage) is the largest among the several major nuclear research centers in West Germany. A major part of the German R&D efforts on gas-cooled nuclear reactors and their power conversion systems, including the closed-cycle gas turbines, has been conducted there. Work relating to the closed-cycle helium turbine for application as a power conversion device for the gas-cooled reactor is coordinated under the HHT-project (High Temperature Reactor with Helium Turbine).

Historically, the German program for helium gas-turbines integrated with a high-temperature reactor (HTR or commonly identified as HTGR in the United States) was initiated at KFA in 1964-65. However, a new set of initials was introduced to the German nuclear vocabulary at the Jülich meeting held in September 1972--the HHT (Hochtemperaturreaktor mit Helium turbine) project was a new name for a system similar to the ill-fated KSH-Geesthacht nuclear gas-turbine plant. A ministerial advisory committee recommended support for the HHT development with its dry cooling towers. Three steps were recommended as follows: (1) design a 300-MWe prototype power plant and conduct a research project in parallel at a cost of 143 million Deutsche Mark (DM) until 1974; (2) make a detailed design evaluation of the economic advantages of the system which could be built at a cost of DM 115 million; and (3) make a decision for construction to begin in 1978. The importance of this project in the German nuclear program at that time was reflected by the presence at the Jülich meeting of the Minister of Science and Education, Dr. K. von Dohnanyi. In his introductory speech, the minister emphasized the Federal Government's intention to go ahead with the HHT project unless strong opposition was expressed at the meeting. As it turned out no such opposition was expressed.

The advanced HHT system has been inspired by the potentially high gas coolant-outlet temperature of the HTR or (or HTGR), as well as the increasing concern for the quality of the environment, particularly the thermal pollution aspect of power stations in Germany. The Germans seem to be convinced that this type power system can produce electric power more economically than other power systems if dry cooling towers are used for heat rejection. This was their major incentive in launching the HHT project in 1972. Their program seems to favor large-output (1100-MWe unit capacity) turbine generator sets with single-shaft design, installed horizontally inside the Prestressed Concrete Reactor Vessel (PCRV) below the reactor core. Contrary to the GA design, they favor the use of an intercooler despite the dry cooling towers. The development of HTR for the generation of process heat was also initiated in 1971 to complement the HHT project.

When the HHT project was launched under the sponsorship of the German Ministry of Research, the partners in this program included BBC, HRB, NUKEM and the KFA. At present there are seven European partners in the HHT Project, KFA,BBC, GHH, HRB, NUKEM all in W. Germany and Sulzer Brothers and Eidgenössisches Institute fur/Reaktorforschung (EIR) in Switzerland. The annual budget for the HHT project is approximately DM 50 million, not including the DM 80 million allocated for the High-Temperature Helium Test Facility (HHV). The total budget for the 1976-77 period is approximately DM 110 million.

The HHV Facility (Hochtemperatur Helium Versuchsanlage), an important part of the HHT project, is located within KFA. It has been designed and built to test crucial components for closed-cycle helium gas-turbine power-conversion systems, - particularly those which would be integrated directly with a high-temperature gas-cooled reactor. It is the only test facility which will enable simulation of gas-cooled reactor thermodynamic conditions in terms of pressures (up to 750 psia), temperatures (up to 1000°C), and mass flows (up to 200 kg/sec). It is regarded as the most crucial test facility for obtaining technical information needed before building the full-scale nuclear- or fossil-powered closed-cycle gas-turbine power plant. The major experimental programs planned for the HHV, and to begin in the spring of 1977 include: 1) turbomachine, 2) gas duct and insulation, 3) valves and armatures, 4) cooling system, 5) helium purification system, and 6) oil system. The construction of the HHV facility was begun in April 1973 and is expected to be completed at the end of 1976.

A schematic flow diagram for the HHV facility is show in Fig. 3. The system lifetime is designed to be 10,000 hours at 850°C maximum temperature or 600 hours at 1000°C. There is no external heat source required for operating the system at these temperatures; the desired operating temperature is achieved by the continuous compressor work input which is provided by a synchronous motor of 45 MWe, and it takes 12 hours to reach the normal operating temperature of 850°C(1562°F). Under the normal operating conditions, the turbine inlet temperature is 850°C (1562°F), and the compressor inlet and outlet temperatures are 770°C (1418°F) and 860°C (1580°F), respectively. The operating pressure at the test section is 51 bar (750 psia). Since the two-stage turbine and the eight-stage compressor are connected by a single shaft driven by the 3000-rpm motor the net shaft-power available for the compressor work is 90 MWe (including a 45-MWe motor and a 45-MW turbine). The total helium volume in the facility is 8000 m^3 at existing pressure and the helium mass flow rate is 250 kg/sec. Heat rejection required from the dry cooling tower is 180 GJ/h (170.5×10^6 Btu/h).

The most important component of the HHV facility is a turbomachine with the basic rotor dimensions equivalent to those for a helium turbine of 300-MWe power rating. The facility will be used starting in 1977 for studying critical components such as shaft seals and bearing as well as their design and operational characteristics, including noise, and vibration among others. The testing of gas piping, including related insulation and noise problems is probably the next most important program for the HHV facility. The gas loop is about 80 long and includes three test sections of 1.5 m diameter and 4.5 m long each one with a fiber insulation and another with a foil insulation, both equipped with thermocouples, stress-strain gauges and sonic probes. The third test section is a coaxial gas duct.

At the time of our visit, construction of the HHV facility seemed to be at least 75% completed, although installation of the major loop including the test sections appeared to be finished. However, the turbomachinery was not yet installed, as it had been shipped to England for coating of turbine blades.

V. Components

The heart of the system is, of course, the helium turbine. One might wonder why it is that these big machines are manufactured in Europe only and not in the US. The answer lies at least in part in the European educational system for craftsmen. It is not a better system, but a different one. It is less flexible and would, for this reason, probably not work in the US. On the other hand, it provides large numbers of highly skilled craftsmen for European industry. Therefore, companies like GHH, Sulzers, or BBC can afford to produce these machines on an individual basis for a very reasonable price. Visiting these companies, one can observe a man machining, almost completely by himself, the rotor of the turbine on a very unsophisticated lathe. The last thirty years have shown that this European advantage is not an important one, since the standard of living of a nation is decided by her ability for mass production. However, with energy having become a major issue in recent times, this may change, since no nation has so far been capable of producing nuclear reactors on a mass basis. If standardization cannot be achieved, the Europeans will have a clear-cut advantage.

In the case of large gas-turbines, however, the story will be different. The difference in designs already makes competition very close. If the future fuel or nuclear situation should favor deployment of large gas turbines, they will very likely be subject to mass production, especially if the marine market should develop.

One major difference in design between the Oberhausen turbine (built by GHH) and those built by BBC is the method by which the individual turbine wheels are attached to each other and to the shaft (hub). The GHH design uses the Hirth-gear, while BBC uses an all-welded design of a proprietary nature.

The other major component is the gas heater, which is, of course, only interesting for fossil-fueled systems. The gas heater used in Oberhausen is a simulator for a nuclear reactor and not really representative of heaters required for fossil systems. However, some of the challenges encountered during the construction of the Oberhausen heater are also valid for these other types: One is materials. Some of the austenic steels were not available in the required shapes, therefore some heater pipes had to be rolled and welded. While efforts were made to do most of the required welding at the factory, 3000 welds still had to be made in the field. Only 10% of these were inspected, a practice which though successful in this non-nuclear application could not be tolerated in a nuclear installation.

The heater tubes which have approximately 50-mm-OD and 3-mm wall thickness are designed to operate at a maximum metal temperature of 800°C (1472°F) so achieving a helium outlet temperature of 750°C (1382°F). The EVO helium heater has a total heat-transfer surface area of approximately 6000 m^2 (64,560 ft^2) and was designed for a lifetime of 100,000 hours. Some other details are as follows: all tubing for the helium heater had to be hung to allow for thermal expansion; tubes were all welded manually through the studs; the Incoloy 807 headers, for the Oberhausen Helium heater have 50 cm (19.7 in.) OD, 3.4 cm (1.34 in.) thickness and 9 m (29.5 ft) long which were welded to a larger header manifold--this, the most difficult manufacturing process, was accomplished by a Scottish manufacturer and the weight of tubing alone for the Oberhausen helium heater is approximately 100 tons. The critical problems of the helium heater include the selection of materials, homogeneous temperature design, high-temperature header fabrication, and the thermal expansion of the tubes and headers. Incoloy 807 has been identified as the best candidate material for the helium heater; Nimonic 263 also seems to have satisfactory properties but is very difficult for tube extrusion.

VI. Conclusions

The new closed-cycle gas turbine technology has been slowly developed over the last 20 years. Even so, as shown in Table I, it is certainly amazing how much has already been done.

For the immediate future (next eight years), a decision will probably be made regarding the European future of the CCGT. From talking with well-informed people, one is led to believe that the marine market will open up in about eight years, notwithstanding the present lull due to overcapacity in ships' tonnage. This means in about four years, European design and sales activities will accelerate in this field, at least for the open-cycle marine gas-turbine.

The future of the central power station CCGT--nuclear or conventional--will also be decided in the not-too-distant future (perhaps, however, longer than eight years). If gas-cooled reactor development and demonstration continue, the commercial closed-cycle gas-turbine may be very much in demand. This hope is buoyed by the emerging need for high-temperature process heat and by the belief that the gas-cooled reactor may contribute to controlling proliferation through operation within the thorium fuel cycle which does not produce plutonium.

Despite the fact that the majority of the CCGTs built so far are for conventional application (fossil-fueled), it is hard to predict whether this type will ever play a major roll. The future of central-station power depends on the availability or non-availability of certain fuels at certain prices, which is very hard to project. Other future problems are whether or not synthetic fuels will become available and what unforseen environmental regulations will impede the direct combustion of coal.

Fig. 1

CYCLE DIAGRAM OF HELIUM GAS TURBINE SYSTEM

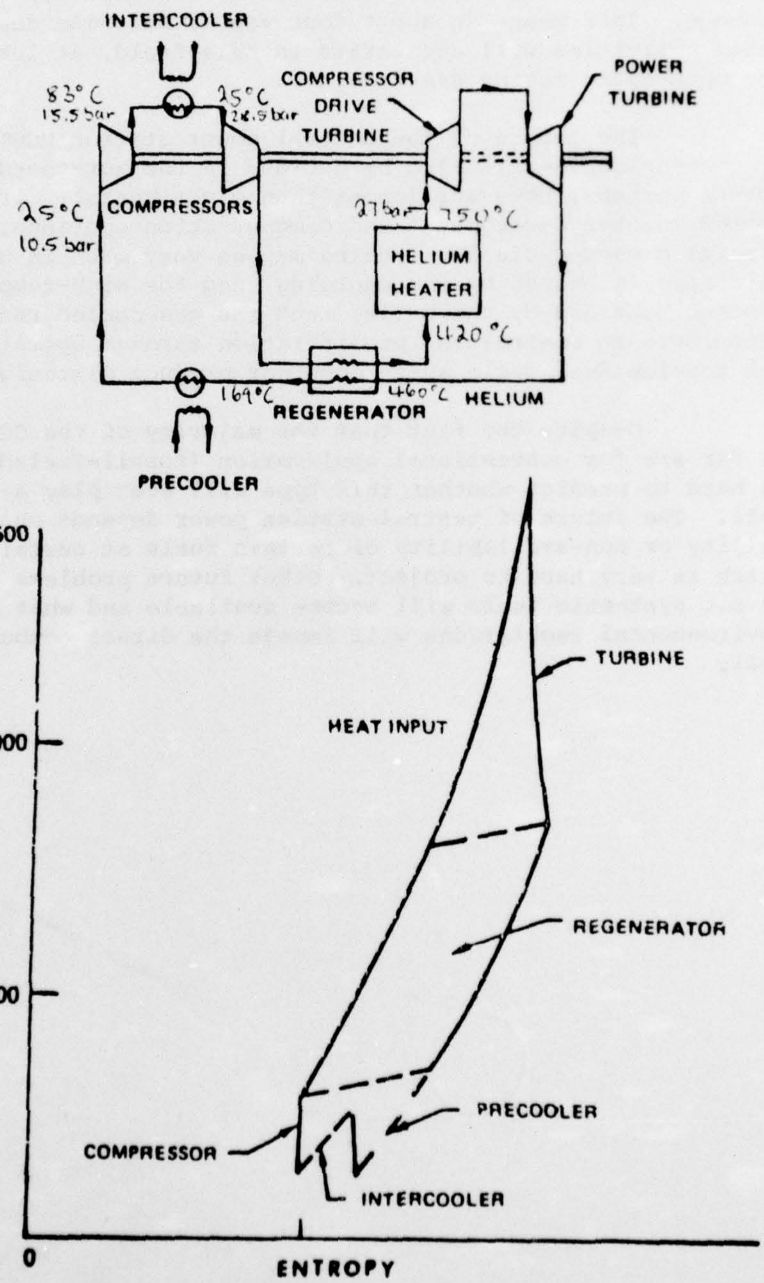

Fig. 2

FLOW DIAGRAM FOR THE HELIUM HEATER

EVO–OBERHAUSEN PLANT

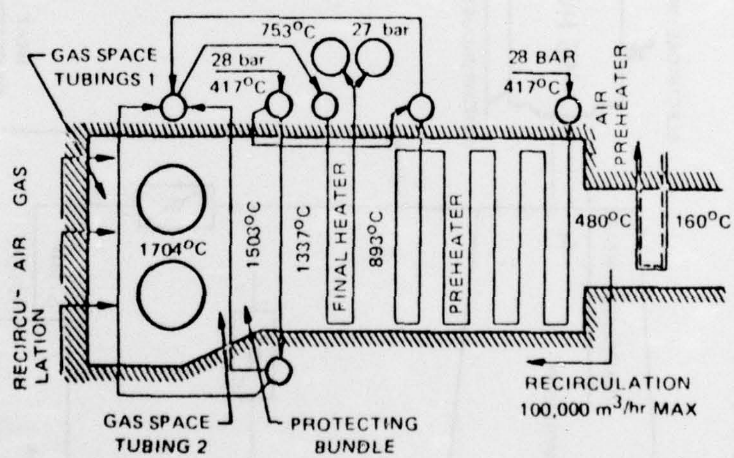

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Fig. 3

HHV (HOCHTEMPERATURE–HELIUM VERSUCHSANLAGE) FLOW DIAGRAM

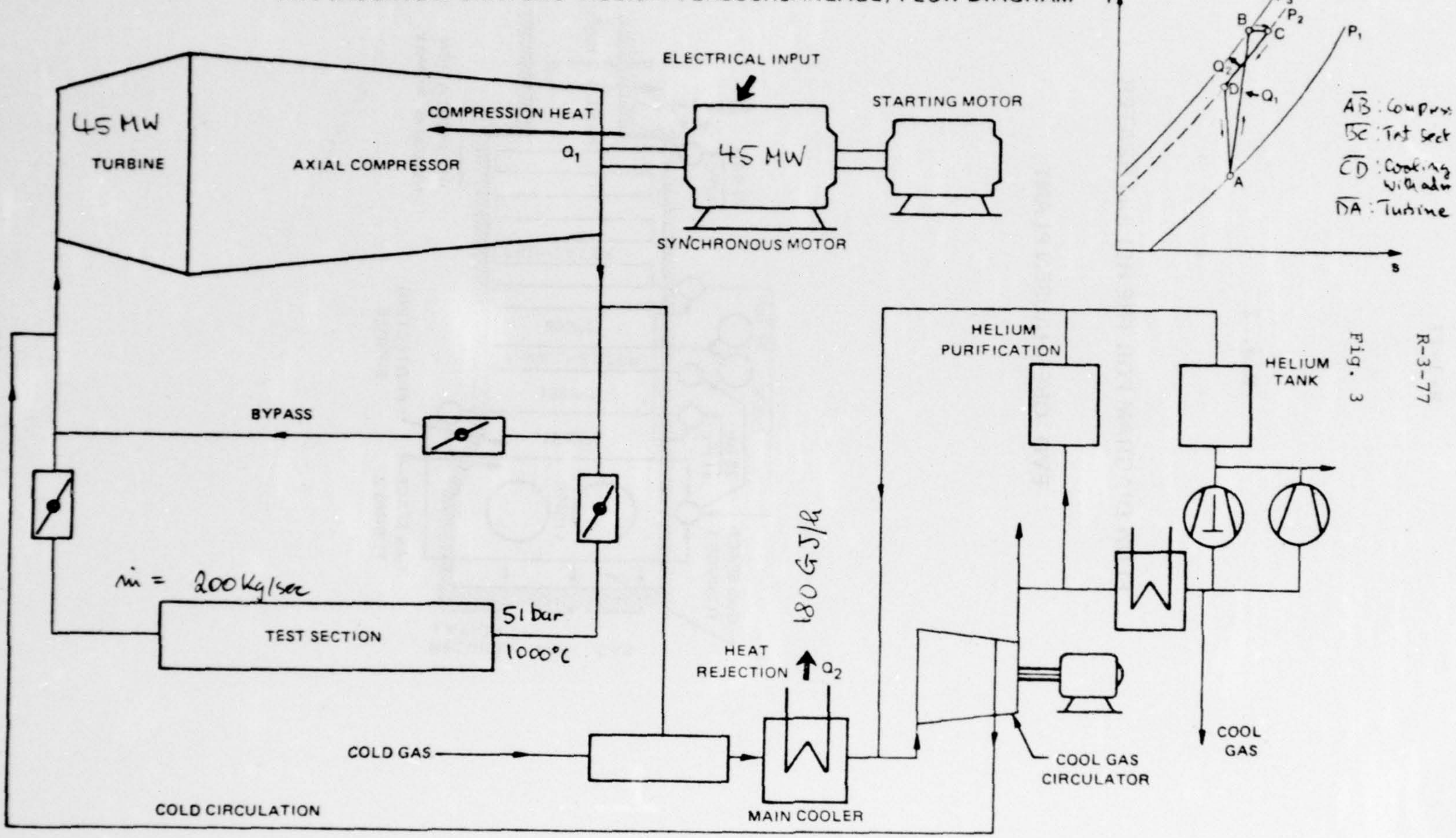

TABLE I. CLOSED-CYCLE GAS TURBINE PLANTS

Plant / Manufacturer / Fuel	Escher-Wyss / Oil	St. Denis / Oil	Ravensburg Germany GHH / Coal	Toyotomi Japan Escher-Wyss / Nat. Gas	Altnabreac / Peat	Rothes / Coal Slurry	Coburg Germany GHH / Coal	Novokaschirsk USSR Escher Wyss / Lignite	Nipon Kokan Japan Fuji Denki / Furnace Gas	Oberhausen I / Coal & Gas	Haus Aden Germany GHH / Gas/Coal	Gelsenkirchen Germany GHH / Gas/Oil	Vienna Austria / Oil	Oberhausen II Germany GHH / Gas
Power MW	2.0	12.5	2.3	2.0	2.2	2.0	6.0	12.5	12.0	14.3	6.4	12.3	30	50
Heat gcal/h			2.1 - 3.5	-			7-14	8-10	-	16(24)	6.7	17.25	40	55.[illegible]
Comp Inlet Temp. °C			20	2.0			20	20	25		20	20	25	25
Comp Inlet Press. bar			7.2	7.2			7.3	7	6.7		9.3	10.2		15.6
Turbine Inlet Temp., °C	650	660	660	660	660	660	680	680	680	710	680	711	720	750
Turbine Inlet Temp., bar	25	55	27	27	27	27	27.5	29	29	32	31	38.5	44	28
Eff. @ Terminals o/o			25	26			28	28	29		29.5	30.8		33
Turbo Set Speed, rpm			12,750	13,000			8,240	6,600	6,600		8,200	6,654		5,500
Alternator Speed, rpm			3,000	3,000			3,000	3,000	3,000		3,000	3,000		3,000
Compressor Type			radial	radial			axi/ radi	axial	axial		axial	axial	axial	axial
Compressor Stages			3	3			6+7+1	9+10	5+5+10		9+6	7+8		10+15+7
Turbine Type			axial	axial			axial	axial	axial		axial	axial		axial
Turbine Stages			5	5			5	6	6		5	6		11
Operation Date	1939	1951	1956	1957	1959	1960	1961	1961	1961	1960	1963	1967	1972	1974
Hours Operation			110,000	780,000			96,000	31.000	38,000		93,000	48,000		3,300